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(54) **Plasma reactor**

(57) The disclosure relates to a gas injection apparatus for injecting gases into a plasma reactor vacuum chamber having a chamber housing (10), a pedestal holding a workpiece to be processed, means for applying RF energy into the chamber, the gas injection apparatus having a gas supply containing an etchant species in a gas, an opening in the chamber housing, a gas feed line (15), from the supply to the opening in the chamber housing, and gas distribution apparatus near the opening in the chamber housing, the gas feed apparatus having at least one slit nozzle (25) facing the interior of the chamber. In a preferred embodiment, the gas distribution apparatus includes a disk member (20a) surrounded by at least one annular member (35a) with a gap (25) therebetween comprising the slit nozzle, the disk member and annular member blocking gas flow through the opening in the chamber housing. Preferably, each of the members of the gas distribution apparatus comprises a material at least nearly impervious to attack from the etchant species. In one example, each of the members of the gas distribution apparatus comprises one of ceramic, quartz, sapphire, polyimide or anodized aluminum and the gas feed line comprises stainless steel. Preferably, each of the members has its surface polished prior to assembly of the gas distribution apparatus.

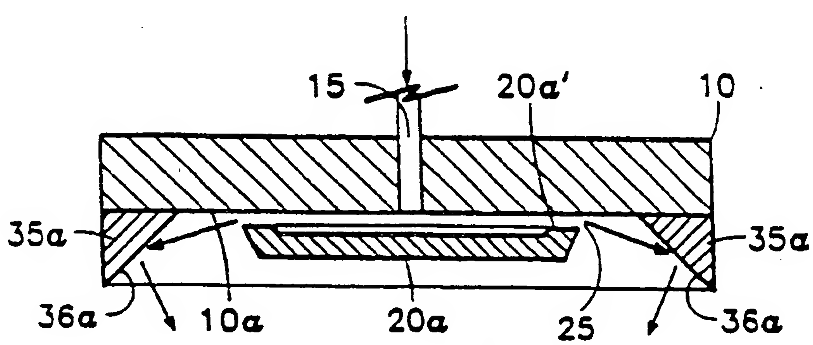

FIG. 1A

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a so-called focus ring, which may be an annular vertical high wall up to several centimeters in height surrounding th wafer periphery. This wall or focus ring stops or retards the replenishment of etchant species at the wafer periphery.

The invention is provided in a gas injection apparatus for injecting gases into a plasma reactor vacuum chamber having a chamber housing, a pedestal holding a workpiece to be processed, means for applying RF energy into the chamber, the gas injection apparatus having a gas supply containing an etchant species in a gas, an opening in the chamber housing, a gas feed line from the supply to the opening in the chamber housing, and gas distribution apparatus near the opening in the chamber housing, the gas feed apparatus having at least one slit nozzle facing the interior of the chamber. In a preferred embodiment, the gas distribution apparatus includes a disk member surrounded by at least one annular member with a gap therebetween comprising the slit nozzle, the disk member and annular member blocking gas flow through the opening in the chamber housing. Preferably, each of the members of the gas distribution apparatus comprises a material at least nearly impervious to attack from the etchant species. In one example, each of the members of the gas distribution apparatus comprises ceramic and the gas feed line comprises stainless steel. Preferably, each of the members has its surface polished prior to assembly of the gas distribution apparatus.

The following is a description of some specific embodiments of the invention, reference being made to the accompanying drawings in which:

FIG. 1A is a cross-sectional view of the ceiling of a plasma reactor including a first embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 1B is a cross-sectional view of the ceiling of a plasma reactor including a second embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 1C is a cross-sectional view of the ceiling of a plasma reactor including a third embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 1D is a cross-sectional view of an embodiment corresponding to FIG. 1C but having a vertical slotted nozzle.

FIG. 2 is a cross-sectional view of the ceiling of a plasma reactor including a fourth embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 3 is a cross-sectional view of the ceiling of a plasma reactor including a fifth embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 4A is a cross-sectional view of the ceiling of a plasma reactor including a sixth embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 4B is a cross-sectional view of an embodiment corresponding to FIG. 4A but having vertical slotted nozzles.

FIG. 5 is a perspective exploded view of a portion of the gas distribution slotted nozzle of FIG. 4A.

FIG. 6A is a cross-sectional view of the ceiling of a plasma reactor including a seventh embodiment of a gas distribution slotted nozzle of the present invention.

FIG. 6B is cross-sectional view of an embodiment corresponding to FIG. 6A but having vertical slotted apertures.

FIG. 7A is an enlarged cross-sectional view of a top-inserted version of a single slot "in-lid" embodiment of the invention corresponding to FIG. 1C.

FIG. 7B is an enlarged cross-sectional view of a top-inserted version of a single slot "in-lid" embodiment of the invention corresponding to FIG. 1D.

FIG. 7C is a cross-sectional view of a two-slit version of the embodiment of FIG. 7A.

FIG. 7D is a cross-sectional view of a two-slit version of the embodiment of FIG. 7B.

FIG. 7E is a cross-sectional view of a three-slit version of the embodiment of FIG. 7C.

FIG. 7F is a cross-sectional view of a three-slit version of the embodiment of FIG. 7D.

FIG. 7G is a perspective view of a central disk of the blocking plate assembly in the embodiment of FIG. 7D.

FIG. 8 is a cross-sectional view of nearly an entire plasma reactor in which the embodiment of FIG. 7A is installed.

FIG. 9 is a graph illustrating etch rate uniformity across the wafer surface as a function of the diameter of the gas distribution slotted nozzle of FIG. 7B.

FIG. 10 is a graph illustrating the effect on etch rate uniformity across the wafer surface of the combination of plural slotted nozzles of different diameters.

FIG. 11 is a graph comparing etch rates across the wafer surface with the focus ring (white square

center disk 50 be formed of a material impervious to attack by the plasma or etchant species in the gas injected into the plasma. A preferred material is ceramic or an insulator such as quartz. As a result, the gases to be injected (such as chlorine or boron trichloride in the cas of an etch reactor) never contact aluminum on their way into the reactor chamber. Specifically, the gas feed line 65 to the cylindrical injection passage 43 is stainless steel, so that the injected gases contact either the steel material of the gas feed line 65 or the quartz or ceramic material of the liner 40 and center disk 50. The foregoing features, including the external polishing of the liner 40 and center disk 50 surfaces and the use of materials such as ceramic or quartz, eliminate the problem of contamination due to corrosion and erosion of gas distribution materials.

FIG. 2 illustrates an embodiment corresponding to FIG. 1A, but without the reflector 35a. The embodiment of FIG. 2 was found to provide a deviation in metal etch rate uniformity across a 200 mm diameter wafer surface not exceeding about 20%, uniformity being defined herein as [(max-min)/2*average].

FIG. 3 illustrates a modification of the embodiment of FIG. 2 in which a disk-shaped injection manifold floor 67 having a center gas outlet 67a therethrough is attached to the bottom of the lid 10 by a truncated conical annulus 68. The blocking plate 20b (from FIG. 1B) faces the bottom of the gas outlet so as to uniformly disperse gases emanating from the gas outlet 67. The embodiment of FIG. 3 was found to provide a deviation in metal etch uniformity across the wafer surface not exceeding about 9%.

FIG. 4A illustrates another preferred embodiment of the invention having a blocking plate assembly 69 consisting of a parallelogramic annulus 70 and a smaller truncated conical center disk 75 (similar to the center disk 50 of FIG. 1C) within the annulus 70, and an outer annulus 77, forming two concentric circular slotted inwardly-angled apertures or nozzles 80, 85. FIG. 4B illustrates a modification to the embodiment of FIG. 4A in which the slotted apertures 80, 85 are vertical and the disk and annuli 75, 70, 77 are cylindrical. FIG. 5 illustrates the blocking plate assembly 69 of FIG. 4A prior to assembly at a point at which all of the interior gas nozzle passages are exterior surfaces of the separate pieces 70, 75, 77, which are polished separately for defect-free surfaces. The separate pieces 70, 75, 77 may be held together by radial spokes 96, the outer piece 77 being fastened by bolts 95, 97 to the lid 10, as will now be described. For this purpose, an injection manifold floor 100 is attached to the lid 10 about an opening 110 through the lid providing access to the passages 80, 85. A recessed ceiling 120 in the lid 10 and the injection manifold floor 100 form a gas injection manifold 125 over the passages 80, 85. The bolts 95, 97 are screwed into threaded holes in the floor 100.

FIG. 6A illustrates an expansion of the concept of FIG. 4A in which the blocking plate assembly 69 is modified to include a pair of concentric parallelogramic annuli 72, 74, providing three circular slotted apertures or nozzles 80, 85, 90 angled inwardly toward the center. In this embodiment, all of the pieces are co-planar with the floor 100. FIG. 6B illustrates an embodiment corresponding to FIG. 6A but having vertical slotted apertures 80, 85, 90.

FIG. 7A is an enlarged view of an embodiment which, like that of FIG. 1C, has a single slotted aperture 60, and is contained entirely within the lid 10, thereby eliminating any need for an attached floor (such as the floor 100 of FIG. 4A) and presenting a flush surface toward the interior of the reactor chamber, a significant advantage. The embodiment of FIG. 7A is a modular self-aligning assembly and requires fewer parts. Each element of the assembly is polished prior to assembly. Also, the liner element 46 is supported by a ledge 91 machined around an opening through the lid 10, which allows installation without removing the lid 10, makes sealing easier, and can more easily accommodate the pressure differential between ambient and the vacuum chamber. Furthermore, the embodiment of FIG. 7A requires no fasteners on the chamber side of the sealing surfaces. A significant advantage is that the modular construction of the gas distribution apparatus of FIG. 7A requires no drilling of gas passage holes, even though it succeeds in providing gas flow nozzles or slotted apertures with a width less than the plasma sheath thickness. In the absence of any necessity of drilling small holes, crystalline materials such as quartz or sapphire may be employed, if desired. Such crystalline materials, if chosen, are highly suitable in corrosive gas environments.

FIG. 7A shows how the gas distribution apparatus is bolted with an exterior mounting ring 137 to the lid 10 and how O-ring seals 140 are employed to block gas flow along undesirable paths. The slotted aperture 60 is between about 20-30 mils wide. FIG. 7B is an enlarged view of one implementation of the embodiment of FIG. 7A, having a vertical gas exit flow (slotted aperture 60). FIG. 7B is also a preferred embodiment.

FIG. 7C is a cross-sectional view of a two-slit version of the embodiment of FIG. 7A and employs the truncated conical center disk 75 and truncated conical annulus 70 of FIG. 4A to form the two slotted apertures 80, 85 extending at an angle relative to the axis of symmetry.

FIG. 7D is a cross-sectional view of a two-slit version of the embodiment of FIG. 7B, in which the disk 75 and annular member 70 are cylindrical and are each contained within the lid 10, the inner and outer slotted apertures 80, 85 extending vertically or parallel to the axis of symmetry of the disk and annulus 75, 70. An outer ring 145 surrounds the outer slotted aperture 85. The annular member 70 of FIG. 7D comprises a pair of annular members 70a, 70b. In a preferred implementation, the pair of annular members 70, 70b may be formed as a single integral member, eliminating the seal between them. In the embodiment of FIG. 7D, the outer ring 145 is L-shaped so that it rests on the ledge 91. The annulus 70 (70b) has plural circumferentially spaced ears 150 extending radially outwardly from its outer circumference

In summary, the data of FIGS. 9 and 10 shows that the etch rate variation from center to the outer middle region of the wafer (i.e., from 0 to 40 mm radial position for 150 mm wafers and from 0 to 60 mm radial position for 200 mm wafers) can be minimized by adjusting the slit diameter(s) The present invention provides etch rate uniformity on a par with that of conventional gas distribution apparatus while providing far greater advantages in resistance to corrosion and ease of assembly, as will be discussed below

Referring again to FIG. 8, in order to decrease or control the etch rate near the wafer periphery, a focus ring 278 may be added surrounding the wafer periphery. The focus ring reduces the flow of etchant species across the chemical boundary separating the plasma region over the wafer center having a scarcity of etchant species ions and the plasma region beyond the wafer periphery having a plentitude of etchant species ions. FIG. 11 illustrates how the addition of the focus ring reduces the etch rate near the periphery of a 200 mm diameter wafer from a high rate of about 860 nm/min (black square curve) to a low rate of about 720 nm/min (white square curve). The fact that the focus ring strongly modulates the etch rate at the wafer periphery implies that etch rate variation across the wafer can be minimized by judicious selection of nozzle diameter(s) combined with focus ring height.

Overall, etch rate uniformity comparable to that achieved with conventional gas distribution plates has been demonstrated with the present invention, while providing far greater advantages in resistance to corrosion. As mentioned hereinabove, conventional gas distribution plate are typically designed with more orifices per unit area over the wafer center to enhance the etch rate at the wafer center. An advantage of the present invention is that, despite having a very small number of slotted aperture nozzles (compared to the large number of small orifices in a conventional gas distribution plate), it inherently delivers sufficient gas over the center of the wafer to achieve the same etch rate uniformity.

FIG. 12 is a bottom view of the circular slotted aperture nozzle 60 of FIG. 1C. FIG. 13 illustrates how the nozzle 60 may be segmented into discrete arcuate subsections 60a-60d, while FIG 14 illustrates how the nozzle 60 can follow a meandering arcuate path 140 having a portion 150 thereof deleted, rather than a circular path. FIG. 15 illustrates how the embodiment of FIG. 14 can be segmented into separate arcuate sub-sections. The embodiments of FIGS. 13-15 could be useful for applications in magnetically enhanced reactive ion etch (ME-RIE) reactors in which the corners between adjacent external magnets of the reactor have somewhat higher magnetic fields and therefore higher etch rates with a uniform etchant gas distribution. This non-uniformity can be compensated by aligning the gaps between adjacent sections 60a-60d of the slotted aperture nozzle 60 over the regions of high magnetic field density. In the case of an ME-RIE plasma reactor, such an alignment is shown in FIG. 15 by indicating in dashed line the relative orientation of the four external magnets 200a-200d of the reactor with reference to the four discrete nozzle sections 60a-60d. It is currently felt that such fine tuning of etch rate uniformity is not necessary.

In the embodiments of FIGS. 1C, 1D, 7A and 7B employing a single slotted aperture 60, the aperture diameter is generally in the broad range of 0.5 inches (1.2 cm) to 6.0 inches (15 cm), although the preferred range is 1.0 inches (2.5 cm) to 2.0 inches (5.0 cm). In the embodiments of FIGS. 4A, 4B, 7C and 7D employing a pair of slotted apertures 80, 85, the outer slotted aperture diameter is generally in the broad range of 3.0 inches (7.5 cm) to 6.0 inches (15 cm) with the preferred diameter being about 4.0 inches (10 cm), and the inner slotted diameter is generally in the broad range of 0.5 inches (1.2 cm) to 2.0 inches (5.0 cm) with the preferred diameter being about 1.5 inches (3.7 cm). In the embodiments of FIGS. 6A, 6B, 7E and 7F employing three slotted apertures 80, 90, 85, the aperture diameters in one example may be on the order of about 0.3 inch (0.8 cm), 1.0 inch (2.5 cm) and 1.25 inches (3.0 cm), respectively, or, alternatively, 4 inches (10 cm), 2.5 inches (6.3 cm) and 1 inch (2.5 cm), respectively.

<u>Advantages of the Invention:</u>

The invention provides a combination of advantages over conventional gas distribution plates. Because it is a modular assembly with separate pieces forming elongate apertures or nozzles with a gap not exceeding the plasma sheath thickness, the separate pieces are polished externally so that no surface imperfections can contribute to degradation or particle contamination in a corrosive gas environment. Moreover, the absence of any drilled holes permits the use of any corrosive-resistant materials including quartz or sapphire as well as ceramics, which, in combination with a stainless steel gas inlet, provides a gas distribution apparatus virtually impervious to attack from corrosive gases. The modular design provides drop-in self-aligning assembly for ease of manufacture. Despite the small number of nozzles compared with conventional gas distribution plates, the invention achieves comparable etch rate uniformity and design versatility while at the same time providing cycle lifetime many times that of conventional gas distribution plates. This in turn provides greater throughput by reducing frequency of production down-time for replacing consumable materials.

While the invention has been described in detail by specific reference to preferred embodiments thereof, it is understood that variations and modifications thereof may be made without departing from the true spirit and scope of the invention.

Claims

1. A plasma reactor comprising:
   a reactor vacuum chamber having a chamber housing;

24. The reactor of Claim 23 further comprising an annular gas reflector surrounding said blocking plate.

25. The reactor of Claim 24 wherein said gas reflector comprises a reflector surface facing and acutely oriented relative to said blocking plate.

26. The reactor of Claim 24 wherein said gas reflector comprises a reflector surface facing and obliquely oriented relative to said blocking plate.

27. The reactor of Claim 1 wherein said slit nozzle has a diameter generally in the range of 0.5 inches (1.2 cm) to 6.0 inches (15 cm).

28. The reactor of Claim 27 wherein said slit nozzle has a diameter in the range of 1.0 inches (2.5 cm) to 2.0 inches (5.0 cm).

29. The reactor of Claim 5 wherein said intermediate slit nozzle has a diameter in the range of 3.0 inches (7.5 cm) to 6.0 inches (15 cm) and said slit nozzle has a diameter generally in the range of 0.5 inches (1.2 cm) to 2.0 inches (5.0 cm).

30. The reactor of Claim 29 wherein said intermediate slit nozzle and said slit nozzle have diameters generally on the order to about 4.0 inches (10 cm) and about 1.5 inches (3.7 cm), respectively.

31. The reactor of Claim 6 wherein said slit nozzle, said intermediate slit nozzle and said outer slit nozzle have diameters on the order of about one of:

(a) 0.3 inch (0.8 cm), 1.0 inch (2.5 cm) and 1.25 inches (3.0 cm), respectively, and
(b) 4 inches (10 cm), 2.5 inches (6.3 cm) and 1 inch (2.5 cm), respectively.

32. A gas injection apparatus for injecting gases into a plasma reactor vacuum chamber having a chamber housing, a pedestal holding a workpiece to be processed, means for applying RF energy into said chamber, said gas injection apparatus comprising:
a gas supply containing an etchant species in a gas,
an opening in said chamber housing, a gas feed line from said supply to said opening in said chamber housing,
gas distribution apparatus near said opening in said chamber housing, said gas feed apparatus having at least one slit nozzle facing the interior of said chamber.

33. The reactor of Claim 32 wherein said gas distribution apparatus comprises:
a disk member surrounded by at least one annular member with a gap therebetween comprising said slit nozzle, said disk member and annular member blocking gas flow through said opening in said chamber housing.

34. The reactor of Claim 33 wherein said gas distribution apparatus is contained within said opening in said chamber housing.

35. The reactor of Claim 33 wherein said gas distribution apparatus is suspended inside said chamber adjacent said opening in said chamber housing.

36. The reactor of Claim 33 further comprising an intermediate annular member surrounding said annular member and separated therefrom by a gap therebetween comprising an intermediate slit nozzle.

37. The reactor of Claim 36 further comprising an outer annular member surrounding said intermediate annular member and separated therefrom by a gap therebetween comprising an outer slit nozzle.

38. The reactor of Claim 33 wherein said disk member and said annular member are cylindrical and concentric with one another.

39. The reactor of Claim 33 wherein said disk member and said annular member are each mutually congruent truncated conical sections.

40. The reactor of Claim 39 wherein said conical sections correspond to a cone whose apex faces toward the center of said workpiece, whereby each slit nozzle directs gas flowing therethrough toward said center of said workpiece.

41. The reactor of Claim 36 wherein said disk member and said annular member are each mutually congruent truncated conical sections.

42. The reactor of Claim 41 wherein said conical sections correspond to a cone whose apex faces toward the center of said workpiece, whereby each slit nozzle directs gas flowing therethrough toward said center of said workpiece.

43. The reactor of Claim 33 wherein each of said members of said gas distribution apparatus comprises a material at least nearly impervious to attack from said etchant species.

44. The reactor of Claim 43 wherein said etchant species comprises at least one of (a) chlorine and (b) boron tri-chloride.

45. The reactor of Claim 43 wherein said material at l ast nearly impervious to attack from said etchant species comprises one of: (a) ceramic, (b) quartz, (c) sapphire, (d) polyimide, (e) anodized aluminum.

process gas into said chamber interior one of (a) generally perpendicularly of said pedestal, (b) angled inwardly and (c) angled outwardly of said central axis.

67. The chamber of Claim 66, further including a focus ring mounted upon said pedestal and adapted to surround a workpiece to be processed and to extend above the position of said workpiece in a manner related to injection device diameter, whereby to improve process uniformity across said workpiece.

68. The plasma reactor of Claim 66, wherein said gas injection device further includes at least one annular ring positioned concentrically with said central element and closely spaced thereto to define said slit passageways.

69. The plasma reactor of Claim 66 wherein said gas injection device comprises an insulating material, and said adjacent wall of said chamber comprises a conductive material.

70. The plasma reactor of Claim 66 wherein said gas injection device is recessed within the upper wall of said chamber.

71. The plasma reactor of Claim 70 wherein said gas injection device further includes at least one annular ring concentrically mounted with said central element and closely spaced thereto to define at least one slit passageway therebetween.

72. The plasma reactor of Claim 71 wherein said central element is a disk whose diameter is at least an order of magnitude larger than the diameter of said channel.

73. The plasma reactor of Claim 71 wherein said central element is a cylindrical element whose diameter is greater than but of the same order of magnitude as the diameter of said channel.

74. The plasma reactor of Claim 70 wherein said gas injection device comprises an insulating material which is generally non-reactive in the plasma environment of the chamber interior.

75. The plasma reactor of Claim 66 wherein said slit passageway is a continuous slit.

76. The plasma reactor of Claim 75 wherein said slit passage way comprises an array of discrete slits.

77. The plasma reactor of Claim 76 wherein said array of discrete slits is symmetrically disposed relative to said central axis.

78. A plasma reactor for use with a source of process gas, comprising:

a reactor chamber having an interior capable of being evacuated, and provided with a channel to permit communication between a source of process gas and the interior of said chamber;

a pedestal adapted to mount a workpiece to be processed;

an applicator for coupling RF energy into the interior of said chamber; and

a gas injection device including at least one solid central element adjacent and across the outlet of said channel, said element being surrounded by at least one annular member having a central axis of symmetry with a gap therebetween to define at least one slit passageway directing the gas toward said pedestal, said central and annular elements otherwise blocking gas flow from said channel into said chamber.

79. The reactor of Claim 78 wherein said slit passageway is oriented to direct the process gas into said chamber interior in a direction generally perpendicular of said pedestal.

80. The reactor of Claim 78 wherein said slit passageway is oriented to direct the process gas into said chamber interior in a direction angled inwardly of said central axis.

81. The reactor of Claim 78 wherein said slit passageway is oriented to direct the process gas into said chamber interior in a direction angled outwardly of said central axis.

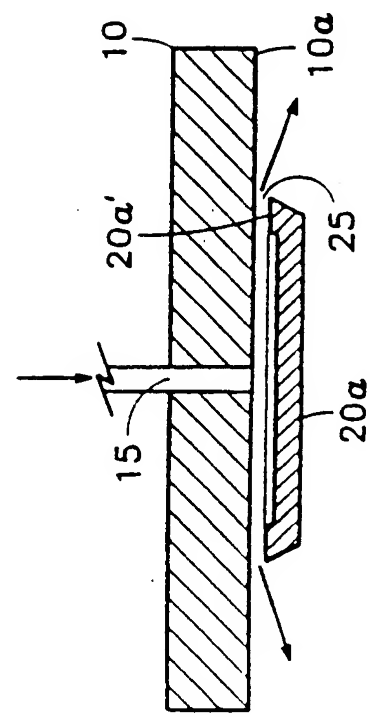

FIG. 2

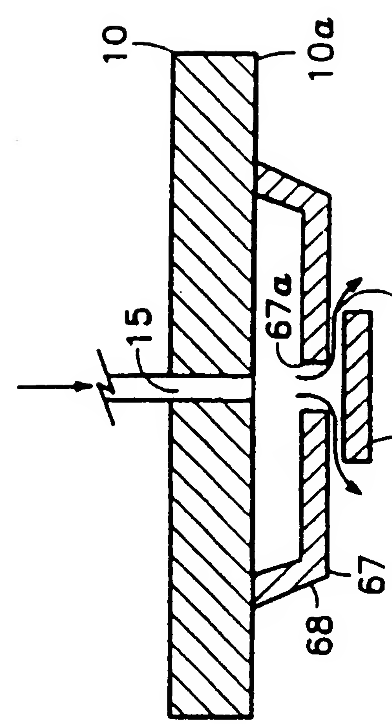

FIG. 3

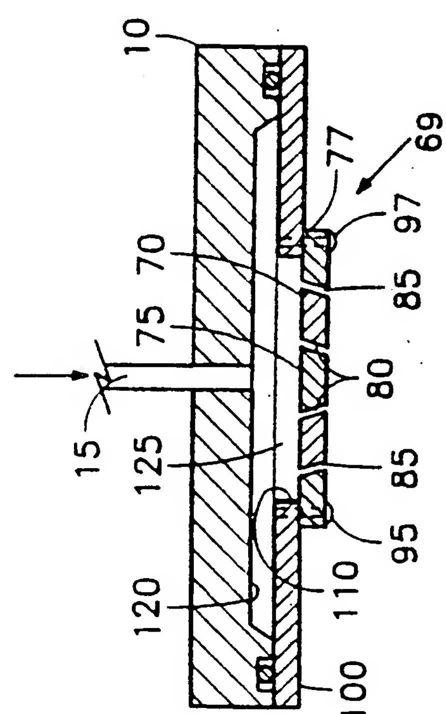

FIG. 4A

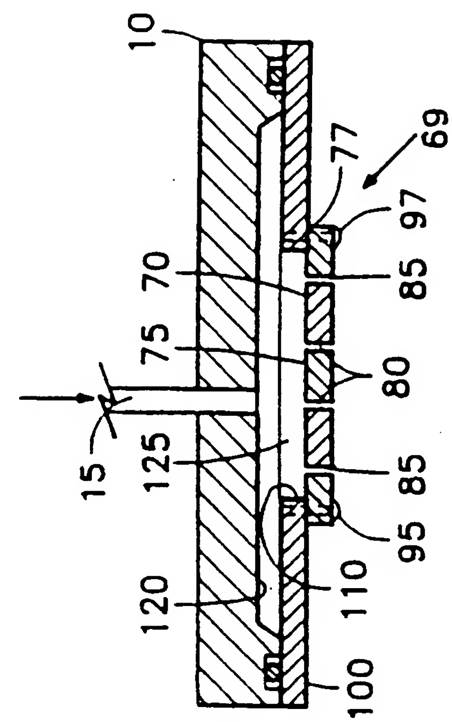

FIG. 4B

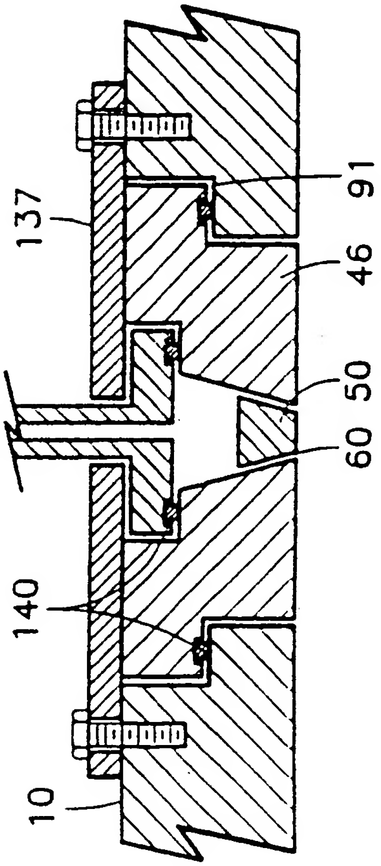

FIG. 7A

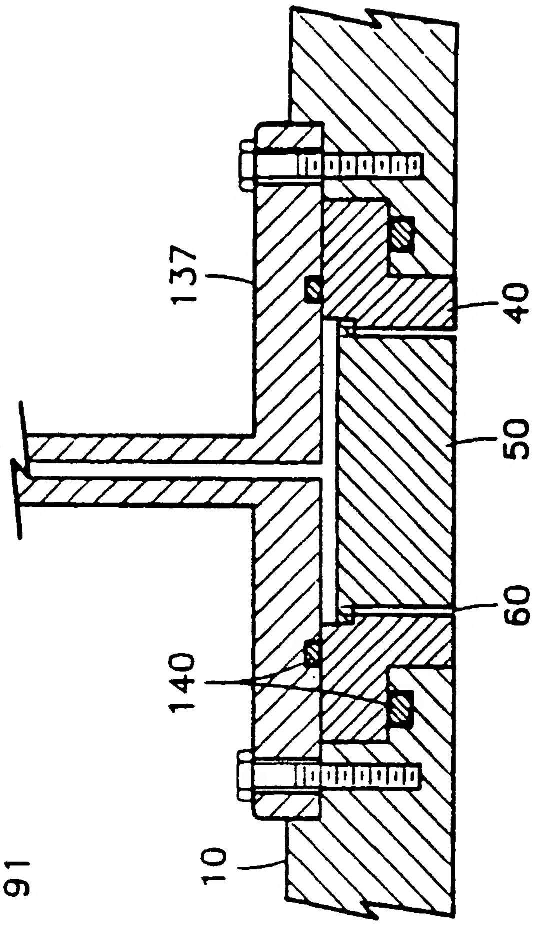

FIG. 7B

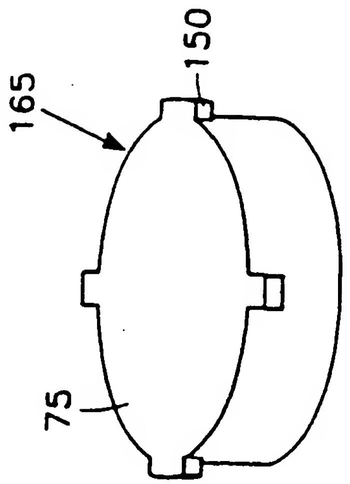

FIG. 7G

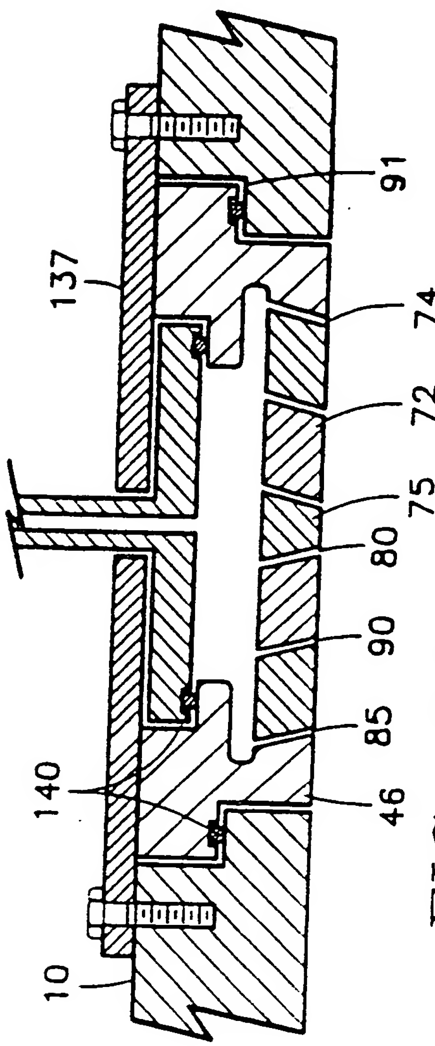

FIG. 7E

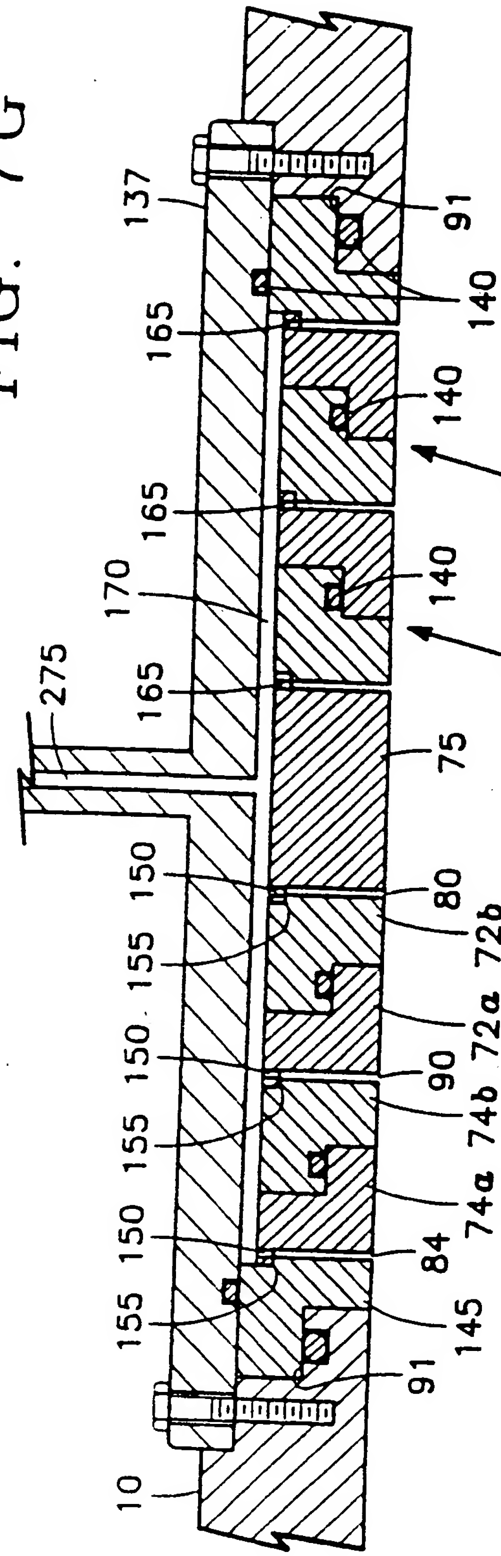

FIG. 7F